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Economics of Wood vs. Natural Gas and Coal Energy in Ohio

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MARCIA GOWEN and FRED HITZHUSEN[1]

INTRODUCTION

Fuel price increases of the 1970's have encouraged Ohio's industrial sector to look for new, less costly feedstocks to substitute for fossil fuels. Enforcement of stricter air pollution standards has speeded up the substitution process. Wood is one feedstock often proposed as an alternative, renewable fuel. Wood's attractive characteristics are its renewability, low sulfur content, and abundant supply, particularly in southeastern Ohio. In contrast to other biomass feedstocks (1, 2, 13, 28, 30, 32), the use of wood as a boiler fuel has received limited economic analysis in Ohio (5). This report compares the use of wood, natural gas, and coal as boiler fuels in three Ohio case plants assuming varying levels of land and air pollution standards. The method of comparison is discounted cash flow financial analysis combined with a constrained optimization model for economic (social costs and returns) analysis.

Natural gas, fuel oil, and coal have been Ohio's traditional boiler fuels since the late 1940's (26). Until the mid 1970's, natural gas and coal were less expensive per energy input than forest chips and almost as low as wood wastes (Fig. 1). However, the 1973-74 oil embargo, natural gas deregulation, and the resulting fuel substitution effects created upward pressure on fuel oil, natural gas, and coal prices. In contrast to fossil fuel prices, the costs for pulpwood or forest chips and wood wastes remained stable over the decade. By the late 1970's, forest chip costs were equal to or below coal costs.

Ohio's industrial energy consumption during the 1970's shows the effect of rising prices on fuel use patterns (Fig. 2). As fuel prices rose, conservation and the effects of stricter air pollution standards caused total energy consumption to fall. Despite the increasing price advantage of coal relative to natural gas as shown in Figure 1, coal consumption declined over the period (Fig. 2). Ohio's Department of Energy suggests that one reason for natural gas or fuel oil users not switching to coal is the uncertainty concerning future levels of land and air pollution standards (26).

Stricter land and air pollution standards are under consideration due to the two social costs associated with coal use—land destruction from surface mining and air pollution. These costs are receiving increased state and federal attention and are slowly increasing market prices through stricter pollution regulations. Forster (8) estimated that the costs of reclaiming surface mined

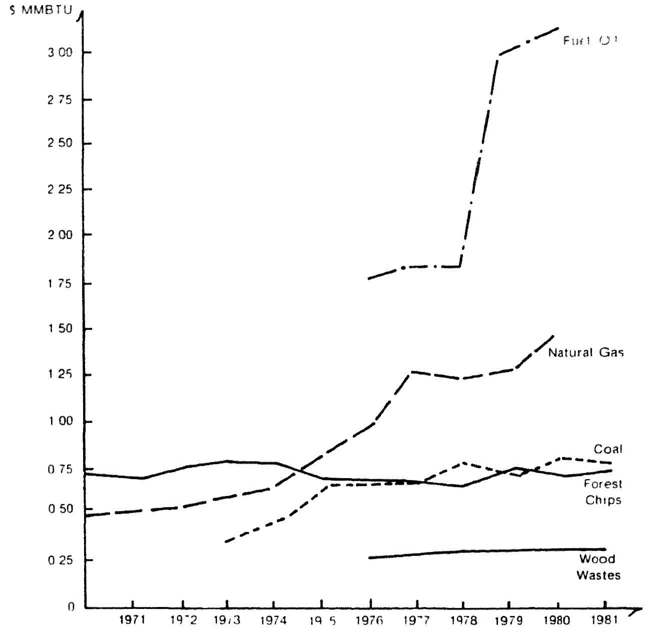

FIG. 1.—Delivered, real fuel prices for industrial users in Ohio (Index: 1970 = 100).

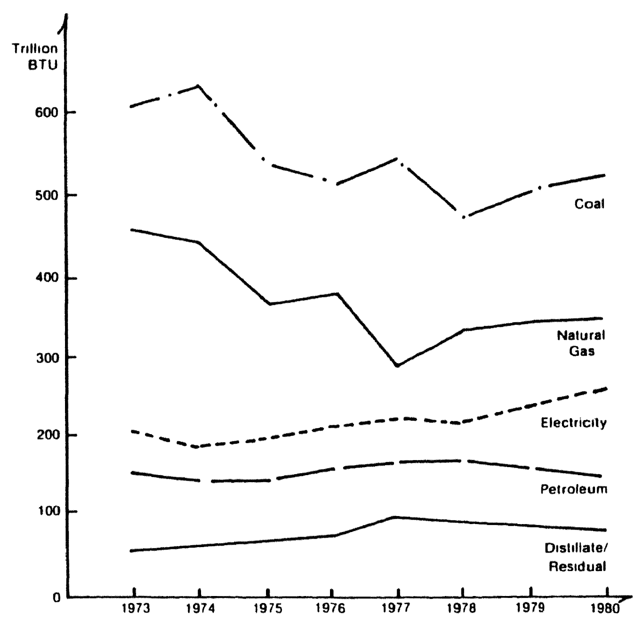

FIG. 2.—Industrial energy consumption in Ohio for 1973-1980.

Source: (26, Appendix B, Table B.1).

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land in Ohio could add $1.03 to $3.64 per short ton to the total costs of coal production. As 71% of the total coal currently used in Ohio is from surface mines, this social cost may be important to coal energy users as well as coal producers (26).

Coal users may also be affected by stricter air quality standards. In the past, Ohio's coal users have faced pollution standards which could be met through mixing low sulfur imported coals with Ohio's high sulfur coal. In many cases, boilers were small enough and/or located in nonmetropolitan areas where mixing was unnecessary. Although coal is still the major industrial energy source in Ohio, a shift in the type of coal burned has occurred over time, reflecting tighter air pollution standards. Low sulfur, imported coal rose as a percentage of total coal use from 47% in 1970 to 55.7% by 1981, with imports coming primarily from the Eastern U.S. (27).

These trends are expected to continue given recent state regulations calling for the use of the "best available control technology" (BACT) on all new boilers and proposed federal regulations calling for a reduction in the permissible particulate and sulfur emissions to 50 to 30%, respectively, of current standards for new boilers producing more than 100,000 lb per hour of steam. As stricter regulations force air pollution compliance costs into the market, more relative price changes will occur between Ohio's high sulfur, cleaned (washed), imported low sulfur coal, and biomass feedstocks.

WOOD ENERGY POTENTIAL

Given the relative fuel prices, potentially stricter pollution standards, and wood's low sulfur content, wood feedstocks could provide private as well as social gains to Ohio's energy users and society. Wood for energy may come from three basic sources: wood manufacturing residues, Ohio's forest lands, and intensively managed wood energy farms. Using 1978 data, a study by Battelle estimated that Ohio's total residues (*e.g.*, sawmill, logging, and unused low-quality wood) would produce 8.34 trillion BTU's annually if fuel prices were high enough to bid all wastes away from current users (12). Given that logging and low-quality wood residues are difficult to collect, sawmill residues are the best short-term sources. However, unused sawmill residues, residues not already used for energy or other markets, are equivalent to only 1.6 trillion BTU's.

The most economical energy feedstock would be low-quality wood from Ohio's forest lands—the small diameter, poor quality wood not used by the sawtimber industry (23). Currently, this wood is used by Ohio's pulpwood industry as wood chips. Annual use in energy equivalents, 4.9 trillion BTU's, is far below annual potential, 159.4 trillion BTU's (10). A third future source of wood energy could come from energy plantations. Few commercial plantations currently exist in the North Central region. Packaging Corporation of America (in Michigan) has the largest plantations in the region with hybrid poplars, and Stone Paperboard in Coshocton, Ohio, has small, test plots of hybrid poplars. Wood chips thus represent the largest near term supply of wood energy in Ohio.

TABLE 1.—A Comparison of Ohio's 1981 Industrial Energy Consumption and Ohio's Biomass Energy Potential (10^{12} x BTU's per Annum).

Use/Potential	Amount
Energy Use*	
Coal†	613.3
Natural Gas	312.5
Electric‡	7.3
Distillate/Residual	47.1
Other Petroleum**	183.1
Total Consumption	1,163.3
Biomass Energy Potential††	
Sustainable Wood	159.4
Municipal Solid Waste	69.0
Usable Crop Residues	64.3
Livestock Wastes	1.4
Total Biomass	294.1

*Source: Tables 3 and 5 (27).

†This coal figure includes the direct use of coal by industry of 437.5 trillion BTU's plus its use in electric generation of 175.8 trillion BTU's. The latter is obtained by taking the percentage of electric generation which coal supplies, 96% in 1981, and multiplying this by the electricity use, 183.1 trillion BTU's (27).

‡To avoid double counting, electric generation figure has netted out the amount coming from coal.

**Other petroleum includes diesel fuel, gasoline, LPG, petroleum coking, and petrochemical feedstocks.

††Source: (14).

Two facts potential energy users want to know are: 1) a realistic estimate of potential wood supply, and 2) a comparison of this wood potential to alternative biomass feedstocks. Hitzhusen *et al.* (14) compiled a county-by-county biomass energy inventory to determine Ohio's biomass potential. As seen in Table 1, the sustainable wood energy potential, net of current pulpwood and sawtimber use[2] is 159.4 trillion BTU's per year or 57% of the total biomass potential. Similar to crops (28), crop residues (1), and solid wastes (32), wood has a regional advantage in Ohio's southeastern forested region.

In comparing wood energy potential to Ohio's industrial energy demand (Table 1), the total potential is 26% of the annual energy supplied by coal and 51% of the energy supplied by natural gas, although the wood supply exceeds the annual distillate/residual oil use. This table suggests that the present sustainable wood supply could not substitute fully for all of Ohio's current industrial energy demands, but it could be used, if economically feasible, as a partial substitute for coal to reduce pollution control costs or to displace natural gas or fuel oil.

[2]In 1978, pulpwood harvest removed about 20 million cubic feet of wood, approximately 22% of Ohio's total timber harvest. Other users of low-quality wood are the chipped board, steel industries, and pallet manufacturers. However, their combined use is less than 4% of Ohio's timber harvest. Pulpwood demand rose from only 4% of Ohio's timber harvest in 1951 to 28% in 1968 and has stabilized since then at approximately 25% or one-fourth of the total harvest in 1978 (23).

Previous research on wood boiler costs in Ohio was made by Cathcart (5). She studied the economic potential of using woodchips in industrial boilers or gasifiers. ODOE (25) has also evaluated the feasibility of producing ethanol from wood in southern Ohio. Cathcart's results suggest that woodchips may have a significant cost advantage to industrial users over natural gas and fuel oil, but be more expensive than coal. The study, however, had important limitations, including limited boiler cost data and a failure to include the social costs associated with wood or coal pollution. This study goes beyond previous work by examining the life-cycle as well as particular social costs of wood and fossil fuel energy use.

OBJECTIVES

The overall objective of this research is to compare wood, natural gas, and coal as boiler fuels under alternative land and air pollution standards. Two types of analyses are made in the study, financial and economic. The financial analysis uses private market valuations of the discounted costs for wood, natural gas, and coal-fired boilers under minimal land and air polution standards. The economic analysis internalizes compliance costs of stricter air pollution control and surface mining reclamation into the discounted cash flows for boilers through use of an integer linear programming or constrained optimization model. The specific objectives of this research are to:

- Estimate the discounted cash flows of wood, natural gas, and coal for three boiler sizes—small, medium, and large—assuming minimal land and air pollution standards, and to compare these discounted cash flows through the use of the net present value and benefit-cost ratios.
- Use an optimization model of discounted cash flows for wood, coal, and wood-coal boilers to internalize air and land pollution costs for a range of air pollution emission levels.
- Conduct sensitivity analyses of fuel price growth and discount rates on the discounted cash flows and make a generalization of the study's implications for Ohio's energy future.

GENERAL METHODOLOGY

Units of Analysis

To conduct the analysis, three case studies of boilers operating in southeastern Ohio are developed. Southeastern Ohio was chosen since it is the major wood producing region in the state. A boiler survey was conducted to provide information on average fuel use, daily swing loads, and fuel storage capabilities. Out of 42 surveys, 25 were returned and provided a diversified sample of Ohio's industries from which to draw case studies. The three case studies used in this research represent small (2.75 MMBTU/hr), medium (41.1 MMBTU/hr), and large (71.1 MMBTU/hr) boilers. These three represent a small private firm, a medium size private industrial plant, and a medium to large size public institution. Annual boiler demand is assumed to be 90, 80, and 80% of capacity for the small, medium, and large boilers, respectively.

The Conceptual Model

To conduct the financial and economic analyses of wood, natural gas, and coal-fired boilers, two quantitative methods are used. First, an unconstrained discounted cash flow analysis is used in the financial analysis to compare life-cycle boiler costs assuming minimal pollution control. Second, a constrained optimization model of coal and wood-fired boilers' discounted cash flows is used in the economic analysis to internalize particular social costs into fuel prices. The use of discounted cash flow life-cycle costs allows sensitivity analyses to be made regarding future fuel prices, thereby capturing a critical variable of uncertainty in the analysis.

The distinction between financial and economic analysis comes from project analysis literature (7, 9, 15, 17, 18, 21, 29). Financial analyses refer to studies of the returns to equity capital for a private investor. In contrast, economic analyses include at a minimum the internalization of some currently uncompensated values society bears or gains from the investment (7, 21, 29).

The distinction between private and social costs may change over time. For instance, in this study's financial analysis, two costs are internalized which have been viewed as social costs. These are annual sustainable forest yields and minimal air pollution compliance costs. Annual sustainable yields are assumed to be maintained through higher transport costs by forest chip users since an industry or institution should not deplete its forest resource base near the installation. Annual sustainable yields mean that yearly harvests do not exceed the annual forest growth or replenishment rates. In the financial analysis, air pollution compliance costs only meet currently mandated standards. The economic analysis internalizes sustainable yields for forest chip use, but also internalizes the costs of coal surface mining reclamation and a range of stricter air quality standards. The latter are internalized through use of an optimization model.

Before describing the calculations of costs in the private and social analyses, an overview of boiler types and costs as examined in this study is shown in Table 2. Generally, any total cost stream for a boiler consists of fuel acquisition costs plus boiler operating/maintenance and capital costs. Three types of boiler fuels can be used—wood, natural gas, and coal.[3] Three forms of wood are analyzed in the study—wood wastes, wood chips harvested from Ohio's forests (forest chips), and wood chips obtained from wood plantations (plantation chips). Wood feedstocks are burned in either combustion boilers or wood gasifiers. Only small and medium gasifier cases are developed due to current size constraints of gasifiers. Direct combustion boilers are

[3]Fuel oil is not considered in this study based upon its small industrial use (3%) in Ohio (26), the fact that many industries which use it do so out of a particular processing necessity, and that Cathcart has already shown fuel oil to be substantially more expensive than wood, natural gas, or coal (5).

TABLE 2.—Combination of Fuels, Costs, Energy Conversion Technologies, and Boiler Sizes Used in Study.

Fuel	Costs: Financial Analysis	Costs: Economic Analysis*	Energy Conversion Technologies	Boiler Sizes
Wood Wastes	Demand, transport Boiler operating Boiler capital	Air pollution	Wood combustion	Small Medium Large
			Wood gasification	Small Medium
Forest Chips	Stumpage, harvest, transport Boiler operating Boiler capital	Sustainable yield Air pollution	Wood combustion	Small Medium Large
			Wood gasification	Small Medium
Plantation Chips	Site preparation, planting, harvest, transport Boiler operating Boiler capital	Air pollution	Wood combustion	Small Medium Large
			Wood gasification	Small Medium
Natural Gas	Acquisition Boiler operating Boiler capital	None	Gasification	Small Medium
Coal	Acquisition Boiler operating Boiler capital	Reclamation Air pollution	Combustion	Small Medium Large

*Plus all costs in Financial Analysis column.

used for all coal systems and gasifiers are used for the natural gas cases.

Cost Estimation

Discounted cash flow or life-cycle cost analysis involves summing over a project or investment life the total expected costs and benefits incurred by the project. These cost and benefit streams are then discounted back to the present and compared. The use of life-cycle costs allows sensitivity analyses to be conducted on key costs or benefits, the expected values of which may vary widely over time. Sensitivity analysis is particularly important to fuel price estimation since past experience suggests that projected prices may differ substantially from actual prices.

The general equation used in the discounted cash flow analysis is that the present value of net fuel savings (P.V.F.S.) equals the present value of costs of displaced fossil fuel minus the present value of wood energy costs. The P.V.F.S. thus compares the discounted costs of the displaced fuels currently being use by industries and institutions (natural gas or coal) to the discounted costs of using wood. The general equation is:

$$\text{P.V.F.S.} = \sum_{t=0}^{20} \frac{C_{jt}}{(1+r)^t} - \sum_{t=0}^{20} \frac{C_{wt}}{(1+r)^t}$$

where:

P.V.F.S. is the present value of fuel savings
j is total costs for fuel j
j is either natural gas or coal
w is wood
t is year t where the project life is 20 years
r is discount rate for year t.

The selection of 20 years as the time horizon is the average boiler life expectancy. Discount rates used in the study are based upon expected rates, with a sensitivity analysis of low, most likely, and high rates being used for fuel prices. The boiler cost streams (C_j's and C_w's) include fuel acquisition costs ($AC_{j,w}$) and energy conversion costs ($EC_{j,w}$). For any time period (t), conversion costs are:

$$EC_{jt} = AC_{jt} + OM_{jt} + DS_{jt}$$

$$EC_{wt} = AC_{wt} + OM_{wt} + DS_{wt}$$

Since three forms of wood are analyzed (wood wastes (WW), forest chips (FW), and energy plantation chips (PW), their acquisition costs are discussed separately later. To compare the fuel cost streams, C_j's to C_w's, two decision criteria are used—the net present value (P.V.F.S.) and the benefit-cost ratio. The benefit-cost ratio is defined as the ratio of discounted fossil fuel costs (natural gas or coal) to discounted wood costs:

$$B/C = \sum_{t=0}^{20} \frac{C_j}{(1+r)^t} \cdot \frac{(1+r)_t}{C_w}$$

Wood Acquisition Costs

The three sources of wood energy differ by their acquisition costs. Wood wastes as defined in this study are the waste material from wood manufacturing firms. Nevel and Redett (23) estimated that 26% of wood waste materials in Ohio was being used as fuel in 1978. Theoretically, the costs of wood wastes should equal the costs of transportation (TC_{WW}) if the buyer does not pick it up, plus a demand premium (DP_{WW}). The demand premium is the opportunity cost of the next best use for the wastes. At present, the costs for wood wastes vary substantially in the state depending upon regional demand. The present value (PV) of acquisition costs for wood wastes (AC_{WW}) can be expressed:

$$P.V.\ AC_{ww} = \sum_{t=0}^{20} \frac{(DP_{WW} + TC_{WW})_t}{(1+r)^t}$$

A Battelle study on wood waste material in Ohio (12) found approximately 1.6 trillion BTU's of unused material. This represents only 1% of the estimated sustainable wood supply from the forest estimated by Hitzhusen *et al.* (14). The limited supply and lower average costs for wood wastes than forest wood chips suggest that wood wastes wil be used first before forest wood chips but will not be able to meet any significant demand.

At present, wood chips obtained through harvesting Ohio's forests constitute the largest potential biomass and wood energy supply (14). Acquisition costs for such chips include a payment to Ohio forest land owners for their wood or what is referred to as stumpage costs (S_{FW}), the costs of harvesting the wood by loggers (H_{FW}), and transport costs for bringing the wood to the energy conversion site (TC_{FW}). The present value of forest chips acquisition costs ($P.V.AC_{FW}$) is:

$$P.\ V.\ AC_{FW} = \sum_{t=0}^{20} \frac{(S_{FW} + H_{FW} + TC_{FW})_t}{(1+r)^t}$$

Stumpage costs (S_{FW}) represent the value of wood in the forest. Theoretically, such prices should include the costs borne by a landowner during a tree's growth as well as any economic rent accruing from the land and wood in terms of future scarcity values. To incorporate the value of sustainability into forest chips' total costs, sustainable yields are accounted for in transportation costs (TC_{FW}) rather than stumpage prices. Stumpage values are taken from timber industry figures adjusted for inflation. Harvest or logging costs (HC_{FW}) used in this research are averages of a 1980 production cost study by Haggard and budgets developed for new logging systems. In Haggard's study of loggers operating in southeastern Ohio (11), the underutilization of equipment and use of older depreciated equipment understated future average costs. To compensate for this bias in Haggard's costs, harvesting budgets are also developed in this study based on new equipment with higher production capabilities (10). Harvest costs include operating/maintenance, labor, debt service on capital, salaries, taxes, and other payments.

As mentioned above, some internalization of future scarcity values (user costs) for overexploitation of the forests need to be internalized into total forest chip costs (16). The maintenance of average annual sustainable yields for Ohio forests is incorporated into transport costs to insure that some scarcity values are approximated. Transport costs are calculated by finding the radius of an area which can provide the case boiler with sustainable annual wood supply. The following formula is used to calculate the sustainable area (A_S) which supplies a given boiler demand (X_S):

$$X_S = A_S\ DY_S\ H$$

where X_S is the annual sustainable production of wood in green tons per year, A_S is the area in square miles, D is the average forest cover density for the area, Y_S is the average sustainable yield for the area, and H represents a forest landowner's annual willingness to harvest chips as a percentage of total commercial wood. Maximum sustainable yields are internalized into Y_S by dividing the average annual chip production per square mile by the average cutting cycle of the dominant pulpwood species.

By incorporating sustainable yields, forest cover density, and landowner attitudes towards harvesting timber into transport distance, a more reliable estimate is made. Actual transport distances are calculated in the study by drawing a series of 3-mile radii concentric circles around installation sites, then adding up the number of rings needed to travel in order to meet annual chip demand (X_S) for the boiler installation. Within each ring, D and H are varied to reflect changing forest cover densities and willingness to harvest as one travels out from an urban center. The sustainable radius (R_S) is then put into the following equation for total transport costs (TC_{FW}):

$$TC_{FWt} = (FC_t = 3/4\ V_t\ R_{St}\ G_t)\ X_{St}$$

where FC are the fixed costs per green ton per mile, V are the variable costs per green ton per mile, and C is the road grid factor adjusting straightline distances by actual transport miles.

A third future source of wood chips may be intensively managed wood plantations. Hybrid poplar or hardwood energy plantations in the North Central region are in the developmental stage, with emphasis still on finding disease resistant, high yielding species. Plantation costs include site preparation and maintenance (SP_{PW}), stocking (ST_{PW}), land (L_{PW}), harvest (HC_{PW}), and transport (TC_{PW}) costs. The present value of plantation wood chip acquisition costs is:

$$P.V.AC_{PW} = \sum_{t=0}^{20} \frac{(SP_{PW} + ST_{PW} + L_{PW} + HC_{PW} + TC_{PW})_t}{(1+r)^t}$$

Cost data are obtained from a recent study at Kansas State University (22), the Packaging Corporation of America in Michigan, and Stone Paperboard of Coshocton, Ohio. These data are average annual costs based on 2-4 year rotations of hybrid poplars.

Optimization Model

Legislation of sulfur and particulate emission limits for boilers has resulted in forcing the private market to incur compliance costs to meet these standards. Coal-burning institutions or industries comply by either blending coals and/or installing pollution abatement equipment. Until recently, blending low and high sulfur coal was often sufficient to meet pollution standards for small or medium-sized boilers (1). However, the stricter air pollution laws recently proposed will necessitate the use of pollution abatement equipment on medium as well as large scale boilers.

To incorporate the shadow values of compliance with stricter air pollution standards, a constrained optimization model based on discounted costs is developed.[4] The objective is to minimize costs subject to meeting: 1) a minimum production of heat, 2) a maximum sulfur emission, and 3) a maximum particulate emission. Costs included are: 1) annualized fixed costs of boilers and pollution abatement equipment, 2) fuel costs, and 3) variable costs of particulate removal. A mixed integer [0,1] linear programming model is developed to internalize these costs. The integer variable model is used to incorporate the fixed cost component and select one type of boiler and pollution abatement equipment.

Important variables in the model are boiler size, fuel type, fuel prices and price growth (determined exogenously), pollution abatement equipment, and length of planning horizon. Two cases are analyzed—a medium (40 MMBTU/hr) and a large (70 MMBTU/hr) boiler located in southeastern Ohio. Two basic forms of fuel can be used, wood or coal. The wood (W) is either wood wastes or wood chips. Three types of coal are available: high-sulfur coal (OC), low-sulfur imported Eastern coal (IC), and cleaned coal (CC).

Because current coal prices are below historic price trends, two sets of prices—current (1982) and historic—are used. Historic prices are the projection of average Ohio and eastern Kentucky price patterns since 1978 into 1982 dollars. Three fuel price growth scenarios are used to understand possible future fuel and pollution abatement equipment mixes. Low, most-likely, and high scenarios, discounted to 1982 dollars, are developed for 1987, 1990, and 1992. The fuel costs used in the model include the average acquisition price plus variable storage and handling costs. Fuel costs are measured as dollars per MMBTU input energy.

Four types of pollution control equipment are available: 1) multicyclone collectors (MC), 2) baghouse filters (BH), 3) wet scrubbers (WS), and 4) electrostatic precipitators (ESP). Three boiler designs are considered for each boiler size: 1) pure wood-fired (W), 2) pure coal-fired (C), and 3) combination of wood and coal (WC). The annual fixed cost for a boiler is included in the objective function.

The constraints of the model are:

Equation	Function
(1)	Minimum annual heat or demand, expressed in MMBTU of output.
(2)-(4)	Air pollution standards. Maximum amount of sulfur and particulate, respectively, emissions allowed.
(5)-(9)	Particulate cannot be treated unless that piece of pollution abatement equipment is used.
(10)-(15)	Fuel for use in a specified type of boiler cannot be used unless that boiler is used, and vice versa.
(16)	Wood alone cannot be used in the wood-coal boiler.
(17)-(19)	Only one type of boiler and of pollution abatement equipment is to be selected.

[4] The model is developed in Gowen (10). The study compares the economics of wood, natural gas, and coal-fired boilers in Ohio.

The variables are:

Z_i = An integer [0,1] variable representing type of pollution abatement equipment.
i = [MC, BH, WS, ESP, 0], with 0 representing no equipment.

B^h, R^h = Two sets of integer [0,1] variables representing type of boiler. h = [W, C, WC].

F_j^h = Amount of fuel of type j used in boiler type h. j = [W, OC, CC, IC]. Note that not every h combines with every j. No wood is used in a coal only boiler. There are eight variables in this set.

V_i = Amount of particulate treated by pollution abatement type i.

The programming model for any period t is:

Minimize:

$$\text{Cost} = \sum_i c_i Z_i + \sum_h c^h B^h + \sum_j e_j \sum_h F_j^h + \sum_i c_i d_i V_i$$

subject to:

$$\sum_{j,h} a_{jH}^h F_j^h \geq H \qquad (1)$$

$$\sum_{j,h} a_{js}^h F_j^h - \sum_i a_{is} V_i \leq S \qquad (2)$$

$$\sum_i a_{ip} V_i \leq P \qquad (3)$$

$$\sum_{j,h} a_{jp}^h F_j^h - \sum_i V_i \leq 0 \qquad (4)$$

$$V_i - \lambda_{1i} Z_i \leq 0 \qquad (5)-(9)$$

for all i

$$F_W^W - \lambda_2 B^W \geq 0 \qquad (10)$$

$$F_{OC}^C + F_{CC}^C + F_{IC}^C - \lambda_3 B^C \geq 0 \qquad (11)$$

$$F_{OC}^{WC} + F_{CC}^{WC} + F_{IC}^{WC} + F_W^{WC} - \lambda_4 B^{WC} \geq 0 \qquad (12)$$

$$F_W^W - R^W \leq 0 \qquad (13)$$

$$F_{OC}^C + F_{CC}^C + F_{IC}^C - R^C \leq 0 \qquad (14)$$

$$F_{OC}^{WC} + F_{CC}^{WC} + F_{IC}^{WC} + F_W^{WC} - R^{WC} \leq 0 \qquad (15)$$

$$F_w^{wc} \leq 0.9H \quad (16)$$

$$\sum_i Z_i \leq 1 \quad (17)$$

$$\sum_h B^h = 1 \quad (18)$$

$$\sum_h R^h \leq 1 \quad (19)$$

where:

$\sum_i c_i Z_i$ = total annual fixed cost of pollution abatement equipment.

$\sum_h c^h B^h$ = total annual fixed cost of boilers.

$\sum_i e_i \sum_h F_i^h$ = total annual variable cost of fuels.

$\sum_i d_i V_i$ = total annual variable cost of pollution abatement.

The strictest federal guidelines proposed for 1985 would limit sulfur emissions to 30% of current standards, now at 4.0 lb per MMBTU input, and particulate emissions to 50% of current levels, with current standards at 0.20 lb per MMBTU input for boilers over 100,000 MMBTU/hour. Because there is a question of actual levels to be enacted and enforced, a range of pollution emissions is developed. The standards are decreased from 100% of current levels to 75, 50, 40, 35, and 30% for sulfur and to 75 and 50% for particulates.

RESULTS OF ANALYSIS

Fuel and Energy Conversion Costs

Before comparing wood, natural gas, and coal energy conversion costs, individual cost streams had to be calculated. As noted earlier, previous research (5) had relied on boiler cost data based on crop residue burning capabilities. An important contribution of this study is to present more complete fuel and wood boiler cost data.

A comparison of fuel acquisition costs by input and output heat content is made in Table 3. All costs represent delivered costs, including transportation, to the boiler installations. Two coal price levels are developed since current prices fall below pre-recession (1982) trends by about $10 per short ton (Appendix B, Table B-II). The pre-recession coal prices refer to projected 1982 prices based on 1978-1981 coal price patterns (10).

As seen in Table 3, wood wastes ($0.97-1.94/MMBTU output) are the cheapest fuels per energy output, followed by coal ($1.70-2.69/MMBTU output), forest chips ($3.27-4.17/MMBTU output), natural gas ($5.00-5.20/MMBTU output), and finally energy plantation chips ($5.38-7.20/MMBTU output). These acquisition price relationships are extremely important to the eco-

TABLE 3.—Fuel Acquisition Costs per Unit of Energy Received and Delivered.

Fuel	Current Unit Price	Cost per BTU Received* ($/MMBTU Input)	Cost per BTU Delivered† ($/MMBTU Output)
Wood			
Wastes	$6-12/gt	0.64-1.28	0.97-1.94
Forest Chips			
Small	$18.33/gt	2.16	3.27
Medium	$21.21/gt	2.49	3.78
Large	$23.37/gt	2.75	4.17
Plantation Chips	$67.40-90.13/gt	3.55-4.75	5.38-7.20
Coal‡			
Ohio High Sulfur			
Current	$31.00/st	1.38	1.72
Pre-recession	$42.12/st	1.88	2.35
Washed Ohio			
Current	$34.20/st	1.36	1.70
Pre-recession	$45.22/st	1.80	2.25
Low Sulfur Eastern			
Current	$43.47/st	1.80	2.24
Pre-recession	$52.04/st	2.15	2.69
Natural Gas**	—	3.90-4.10	5.00-5.20

Sources: Tables 3 and 7; gt = green ton, st = short ton.

*Average heat contents of Ohio high sulfur, cleaned, and Eastern low sulfur coals are 22.4, 25.1, and 24.2 MMBTU/short ton (27). BTU received is the fuel's input energy content before conversion.

†Wood boiler efficiency is 66%; thus received or input heat must be adjusted by 0.66; coal efficiency is 0.80 and natural gas is 0.78. BTU delivered is the output or actual usable energy produced by a conversion system after accounting for conversion inefficiencies.

‡Coal prices are obtained from ODOE, coal companies, and case study users (Appendix B, Table B-II).

**Natural gas prices used in the table are actual 1982 case study prices.

TABLE 4.—Annual Capital, Operations/Maintenance, Labor, and Fuel Costs for Wood, Natural Gas, and Coal-Fired Boilers by Boiler Sizes.

Boiler Size and Annual Costs	Wood Combustion	Wood Gasification	Natural Gas	Coal
	$1000/year			
Small (2.75 MMBTU/hr.)				
Capital*	50	28	24	58
OM	20	6	10	20
Labor	40	5	20	40
Fuel†	72 (43 5)	72 (43.5)	99	33 (48)
Medium (40.1 MMBTU/hr.)				
Capital*	320	208	218	420
OM	200	50	150	150
Labor	200	160	100	200
Fuel†	1,068 (778)	827 (603)	1,554	517 (693)
Large (71.1 MMBTU/hr.)				
Capital*	584	—	—	729
OM	375	—	—	375
Labor	200	—	—	200
Fuel†	1,879 (980)	—	—	871 (1,168)

*Annual capital represents equal annual payments on debt service assuming 15% interest on equipment (equipment mix and costs are found in Appendix Table B-III).

†Wood costs in parentheses are for wood wastes; for coal, the costs in parentheses indicate costs if pre-recession price trends had been maintained in 1982.

TABLE 5.—Decision Criteria for Financial Analyses of Wood vs. Natural Gas or Coal Boilers by Sizes Using Most Likely Fuel Price Projections*.

Wood Fuel, Decision Criteria, and Conversion Processes	Natural Gas		Coal (Current)†			Coal (Pre-recession)*		
	Small	Medium	Small	Medium	Large	Small	Medium	Large
Forest Chips								
Direct Combustion								
NPV ($1,000)	3,409	45,135	−481	−11,699	−25,646	−119	−4,777	−17,166
B/C	2.32	2.39	0.81	0.64	0.57	0.95	0.77	0.71
Gasification								
NPV ($1,000)	4,138	52,560	247	−4,275	N.A.	609	−23	N.A.
B/C	3.23	3.10	1.13	0.83	N.A.	1.33	0.99	N.A.
Wood Wastes								
Direct Combustion								
NPV ($1,000)	4,205	59,922	314	3,088	5,479	677	7,339	19,318
B/C	3.35	4.39	1.17	1.18	1.20	1.38	1.42	1.54
Gasification								
NPV ($1,000)	4,934	63,497	1,043	6,662	N.A.	1,405	10,913	N.A.
B/C	5.65	5.50	1.98	1.47	N.A.	2.33	1.77	N.A.

*Assumes a 13% discount rate, 8 and 10% annual inflation rates for years 1-9 and 10-20, respectively, and most likely fuel price growth projections for wood, natural gas, and coal. Most likely real price growth projections for wood are 0 and 2% per year for years 1-4 and 5-20, respectively; 12, 16, and 12% per year for years 1-4, 5-9, and 10-20, respectively, for natural gas; and 5 and 7% per year for years 1-4 and 5-20 for coal.

†Current coal prices assumes $1.38/MMBTU input in the base year.

‡Pre-recession coal prices assume $1.81/MMBTU input in the base year.

N.A. means analysis was not made due to technological constraints.

nomic feasibility of the particular fuel. For instance, the lowest forest chip price is more than one and one-half times the cheapest coal price per energy output. This suggests that there need to be: 1) substantial savings in boiler operating and/or capital costs, 2) high social benefits from using wood as a sulfur reducing fuel with coal, and/or 3) future cost reducing technology in chip harvesting for forest chips to compete with coal.

First-year average boiler costs (Table 4) indicate that there are no substantial cost differences between wood and coal fired boilers. Significant boiler cost differences appear between wood combustion vs. wood gasification systems, with the latter being cheaper. Like wood gasification, natural gas boiler costs are almost half those of coal or wood combustion systems, but natural gas fuel costs are the highest among the three feedstocks. Because expected fuel prices are critical to the long-run feasibility of a fuel, three fuel price growth scenarios (low, most likely, and high) are developed based on studies by the U.S. Dept. of Energy, Chase Econometrics, DRI, and Ohio DOE (Appendix A). An annual inflation rate of 8% for years 1-10 and 10% for years 10-20 is used with a set of four discount rates — 10, 13, 15, and 25%. The results reported in the following section are based upon 13% discount rates, giving approximately a 5% real annual rate of inflation.

Financial Analysis of Boilers

The private cost analysis compares wood combustion and gasification to natural gas or coal's discounted costs assuming only minimal pollution control and the maintenance of sustainable yields for forest chips. Minimal pollution equipment means no equipment for the small boiler, a multicyclone collector for the medium wood combustion and coal boiler, and a series of cyclone collectors for the large wood and coal combustion boilers.

The results of the financial or private market analyses are shown in Table 5. The net present value (NPV) and benefit cost ratios (B/C) are used as economic decision criteria when either forest chips or wood wastes are used as boiler fuels. The net present value determines fuel cost savings from using wood (fossil fuel cost minus wood fuel costs) and the benefit-cost ratio compares fossil fuel costs (numerator) to wood fuel costs (denominator).

Wood's strong comparative advantage over natural gas can be seen in the first two columns of Table 5.[5] All net present value decision criteria for both wood wastes and forest chips are quite positive for both direct combustion and gasification. The benefit-cost ratios (B/C) range from 2.32 to 5.65 for wood combustion or gasification vs. natural gas boilers. The internal rates of return (IRR) for all wood vs. natural gas systems (not reported in the table) are more than 200% due to constant positive net cash flows throughout the project life.

Besides the advantage of wood over natural gas, another pattern in Table 5 is the advantage of wood gasification over wood combustion. For all boiler sizes and wood wastes or forest chips, the NPV's and B/C ratios are higher for wood gasification than wood combustion systems. These results suggest that wood gasification, if technological improvements occur in its operations, could be the less expensive wood technology. A further pattern seen in Table 5 is the financial attractiveness of wood wastes over forest chips.

Whereas wood is quite competitive with natural gas, the criteria in Table 5 give more mixed results for the economics of wood wastes or forest chips over coal. Wood wastes are definitely more attractive than coal. In general, however, the criteria do not favor forest chip use over coal assuming either current or pre-recession coal prices.

As seen by B/C ratios under one and negative NPV's, direct combustion of forest chips is uneconomical compared to coal combustion for all boiler sizes at a 13% discount rate, even when pre-recession coal prices are assumed. In the small boiler, forest chips might be marginally competitive with coal only if pre-recession coal prices are exceeded. Since the net present value is a negative $119,000 and the benefit cost ratio is 0.95 assuming higher coal prices, forest chips are currently uneconomical compared to coal. Even when the discount rate is raised to 15 or 25% in the most likely fuel price growth scenario, wood combustion of forest chips vs. coal show negative net present values and B/C ratios less than one. At high fuel price growth rates and a low discount rate (10%), coal is still more attractive than forest chips for the small boiler case study.

The results for the medium and large boilers also imply that forest chip combustion is not financially competitive with coal boilers at current or pre-recession coal prices using 13% discount rates (Table 5). Even when sensitivity analyses of: 1) fuel price growth (low and high), 2) coal prices (current or pre-recession), and 3) discount rates (10, 15 and 25%) are made, forest chips burned in the medium or large wood combustion boiler never become a financially attractive alternative to coal assuming minimal pollution control equipment.

Whereas the feasibility of wood combustion over coal gave mixed results depending upon the wood fuel used, wood gasification is more consistently competitive with coal. Small scale wood gasification is financially quite attractive with wood wastes, but also competitive with coal if forest chips are burned. In the medium boiler, wood wastes are also competitive with coal. However, forest chips burned in the medium-scale wood gasifier show negative NPV's and B/C's below one (Table 5). The financial feasibility of the medium size gasifier becomes almost feasible, $-23,000 (NPV) and B/C = 0.99, when higher or pre-recession coal prices are used. In the sensitivity analysis, use of a 15% discount rate with pre-recession coal prices gave a positive NPV and B/C ratio of 1.03. These results suggest that wood gasification of forest chips may be competitive with coal if higher coal prices return.

[5] The financial analyses used COMPRAN, a computerized project analysis program, developed by McCullough and Hitzhusen (19).

Break-even Price Analyses

Another method of comparing the economics of wood to fossil fuels is to determine the wood fuel price, which just makes the discounted cost streams of wood conversion equal to fossil fuel conversion. The "break-even" price gives the value where one is financially indifferent between using wood or the alternative fuel, assuming in this study the most likely fuel price growth and a 13% discount rate. This break-even wood fuel price then is compared to the current or going market price for wood. The spread between this break-even price for wood and current wood prices shows the margin, making wood either economically feasible or infeasible as compared to coal or natural gas.

The wood break-even price "curves" are shown in Figures 3 and 4. These curves give the break-even price for wood combustion or gasification boilers vs. natural gas or coal boilers. In Figures 3 and 4, the range or value of current market wood prices for the three types of wood resources: wastes, forest chips, and plantation chips, are also drawn. As long as the current market price line (or area) for wood is below the wood break-even price curve for a specific type of wood vs. fossil fuel conversion, wood is financially feasible.

As seen in Figure 3, natural gas is always more expensive than wood wastes, forest, or plantation chips since the wood vs. natural gas break-even curves are higher than the current price lines (area) for all wood fuels. The apparent plantation chip feasibility over natural gas is somewhat tenuous given the limited data on which plantation costs are based. In general, this figure strengthens the results shown in Table 5 and stresses that replacement of natural gas by wood as a boiler fuel yields positive cost savings.

Wood vs. coal, however, shows a different relationship (Fig. 4). Given that the current market price for wood wastes is below the discounted break-even prices of wood vs. coal, wood wastes are financially attractive when compared to coal at current or pre-recession prices. According to Figure 4, chips might possibly be economical in the small gasification system at the lowest projected plantation chip costs. As noted above, these plantation costs are projected estimates, and thus only suggestive at best given the limited economic

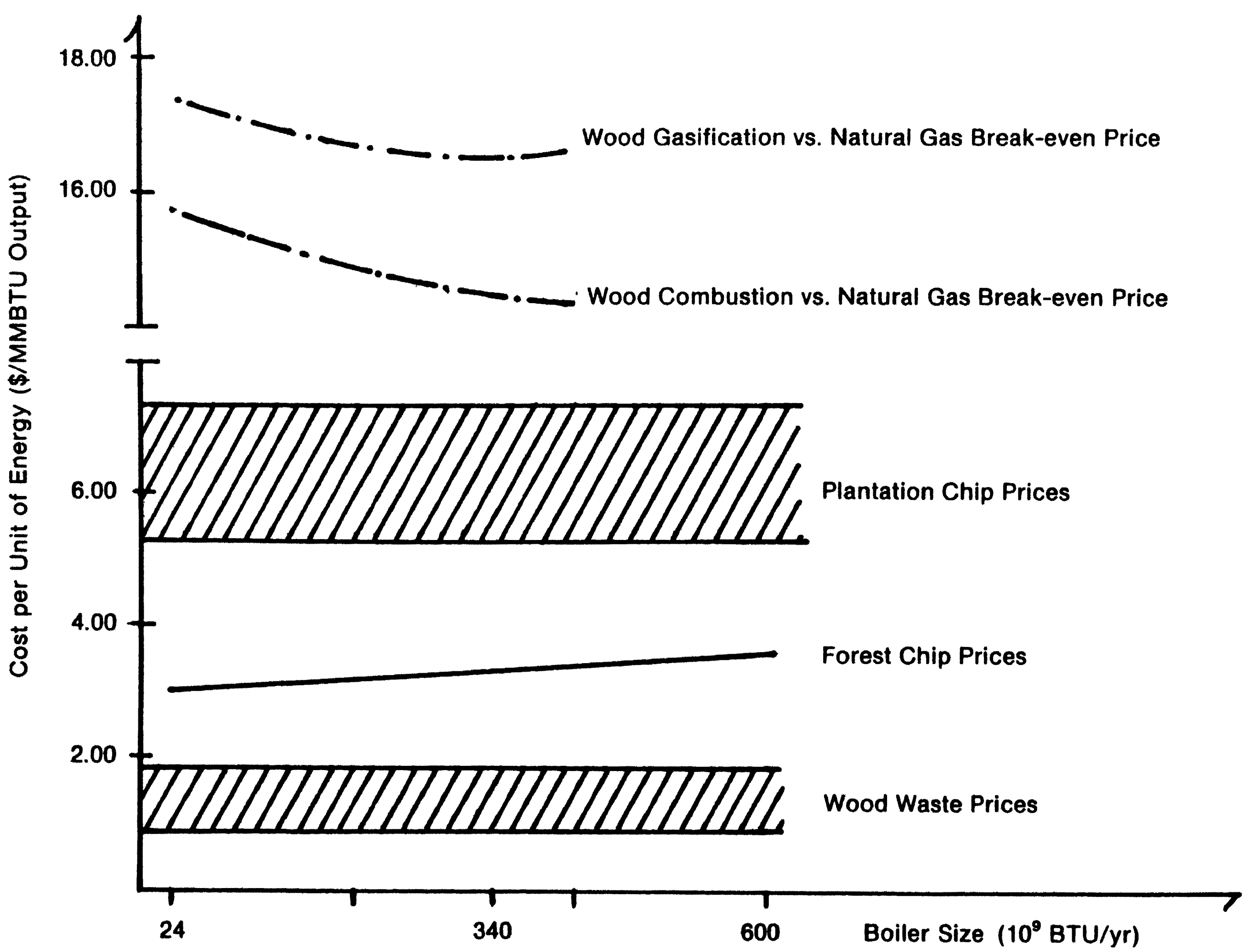

FIG. 3.—Wood vs. natural gas break-even prices as compared to current wood wastes, forest chip, and plantation chip prices.

analysis on which they are based.

As with the decision criteria presented in the previous section, forest chip feasibility is more variable than wood wastes when compared to coal. For the small boiler, the wood combustion system appears competitive with coal at pre-recession prices when comparing the current market price line of forest chips to the break-even wood combustion vs. coal curve. Likewise, in the small and medium-scale boilers, the wood break-even price curve in Figure 4 indicates that forest chips used in gasifiers should be more economical than coal. These results contrast to the results of the financial analysis for the medium gasifier and small combustion boiler (Table 5), where coal at pre-recession prices was marginally more attractive than forest chips. This discrepancy appears to be the difference between comparing first-year break-even prices with discounted cash flows.

Fuel Price and Discount Rate Sensitivity Analyses

Sensitivity analyses on fuel prices and discount rates are also made in the study. Three series of fuel price projections are used—low, most likely, and high. As described earlier, fuel price growth rates for wood, natural gas, and coal are assumed to be interdependent, as reflected in Appendix A. The low price scenario reflects very slow fuel oil and natural gas price rises over the next decade. The most likely price scenario assumes that gas deregulation continues at current levels along with gradual fuel oil price increases. High price projections are realistic only if the deregulation of natural gas is speeded up and fuel oil costs shoot up in the coming years, perhaps due to an embargo.

The sensitivity analyses on fuel prices and discount rates in both types of wood conversion technologies as compared to natural gas boilers do not alter the financial viability of wood over natural gas. Even when low price scenarios and high discount rates are used, the NPV's and benefit-cost ratios become less favorable towards wood vs. natural gas than in the most likely price scenario, but they remain positive and greater than one, respectively.

The effects of changing fuel price growth rates and discount rates on the financial feasibility of wood vs. coal are more mixed, particularly when using pre-recession coal prices. Wood wastes always remain financially viable in wood combustion and gasification units when compared to coal, even when both wood prices and the discount rates are raised and coal prices are lowered. If forest chips are burned in any of the

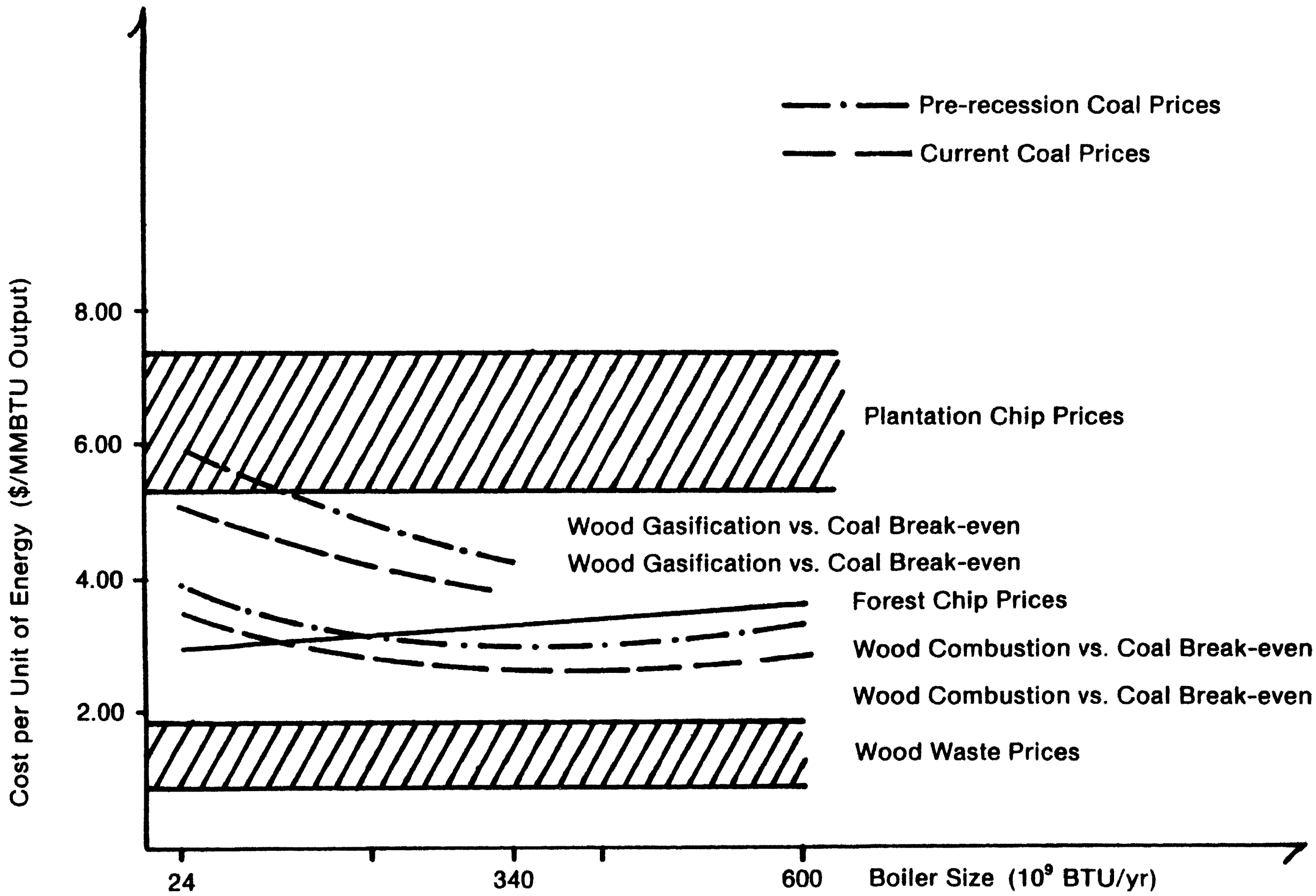

FIG. 4.—Wood vs. coal break-even prices as compared to wood wastes, forest chip, and plantation chip prices.

combustion boilers, their costs are still not competitive with coal even when: 1) pre-recession coal prices are assumed, 2) a high fuel price growth scenario is projected, and 3) a low discount rate (10%) is used.

In the small gasification boiler, forest chips are still competitive with coal at a 10% discount rate, assuming low price growth for wood or coal and pre-recession coal prices. At pre-recession coal prices and a 15% discount rate, the benefit-cost ratio of forest chips in the medium gasifier vs. coal goes to 1.03 (as compared to 0.99 in the most likely scenario assuming 13% discounting). The medium wood gasification unit thus becomes competitive with coal in either a low or high price growth scenario at a 15% discount rate if pre-recession coal prices are used. Except for this case, the sensitivity analyses tend to only further underscore the stability of the earlier results.

Economic Analysis of Boilers

Minimal land or air pollution compliance costs may not reflect future regulatory conditions faced by Ohio boiler users. In contrast to the above analysis, a range of stricter air quality standards and the inclusion of coal's reclamation costs are internalized into an optimization model of wood, coal, and wood/coal boilers' discounted costs. The optimization model presents the boiler manager with the choice of using wood or coal (Ohio high sulfur, cleaned, or imported low sulfur) and various pollution abatement equipment with which to meet a given sulfur and particulate emission level. A range of pollution levels is developed to determine the effects on optimal fuel mix and costs due to varying pollution standards.[6]

Given that only one type of wood feedstock, either wood wastes or forest chips, is available as a potential wood fuel in the model, the results can be discussed separately by type of wood fuel. Due to low wood waste costs relative to all coal costs, only wood wastes are used when the model compares wood wastes vs. coal. When

[6]In this study, optimal solutions, *i.e.*, the optimal fuel mix, boiler type, pollution equipment, and total costs, are determined for various project years. Current and historic coal prices are used to see how such prices affect the optimal solution over time. The results reported in the tables assume the most likely fuel price projections (Appendix A) and a 13% nominal discount rate. Although low and high fuel price growth projections were also conducted, the results' stability at the varying growth levels makes reporting the most likely fuel projections adequate. The results are for the third project year, 1985, the year federal standards are expected to change although models were also made for 1987, 1990, and 1992. The exceptions to fuel mix stability over time are mentioned where appropriate.

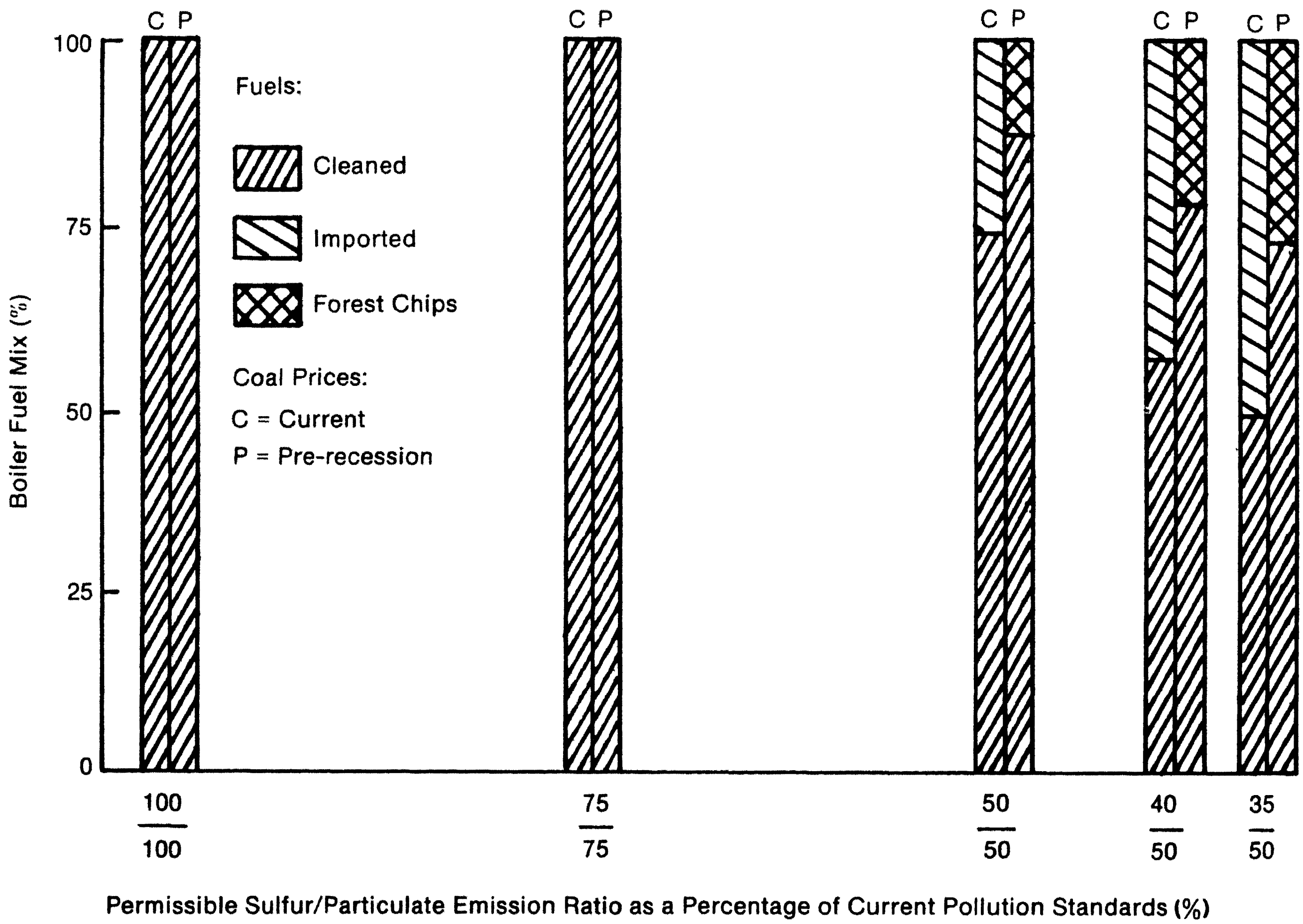

FIG. 5.—Optimal medium boiler fuel mix as a percentage of current air pollution standards.

burning wood wastes, a baghouse filter is used for both the medium and large boilers as the optimum pollution control equipment. Total annual costs for a wood waste-fueled boiler are low relative to the solutions where coal or wood and coal are used. The lower costs result from cheaper fuel and pollution control equipment costs. These results stress that wood wastes are the most economical boiler fuel not only from a private but also from a social perspective.

Unfortunately, the supply of wood wastes is limited, suggesting that a high wood energy demand will bid up their value until they equal, at a minimum, forest chip costs. Thus, analyses using forest chips as the potential wood boiler fuel may provide more insights into the real potential of any significant wood energy market in Ohio.

The results of the social cost analysis for the medium boiler with forest chips as the wood feedstock are shown in Figures 5 and 6. These figures show how the optimal fuel mix (Fig. 5) and total annual costs (Fig. 6) change given varying air pollution standards. Both tables are based on data in Appendix C. In Figures 5 and 6, the two base year coal price levels are presented by the current or pre-recession lines or bars.

Looking at Figure 5, it is evident that coal prices and standards have an important impact on wood fuel use as well as optimal fuel mix. In examining fuel mix changes given current coal price levels, it appears that the shadow-priced value from wood's lower sulfur content is insufficient to make chips economical given coal's lower prices. Even at 35% of current sulfur standards, chips do not enter the solution when assuming current coal price levels. When the model is run for 1987, 1990, and 1992 using current coal prices, wood also never entered the solution at the 100 and 75% standards. Wood also never entered at stricter standards (50, 40, and 35%) in 1990 and 1992. In the fifth project year (1987), wood chips did enter the solution, with cleaned coal providing 13, 23, and 28% of the total heat at 50, 40, and 35% standard reductions, respectively. These results

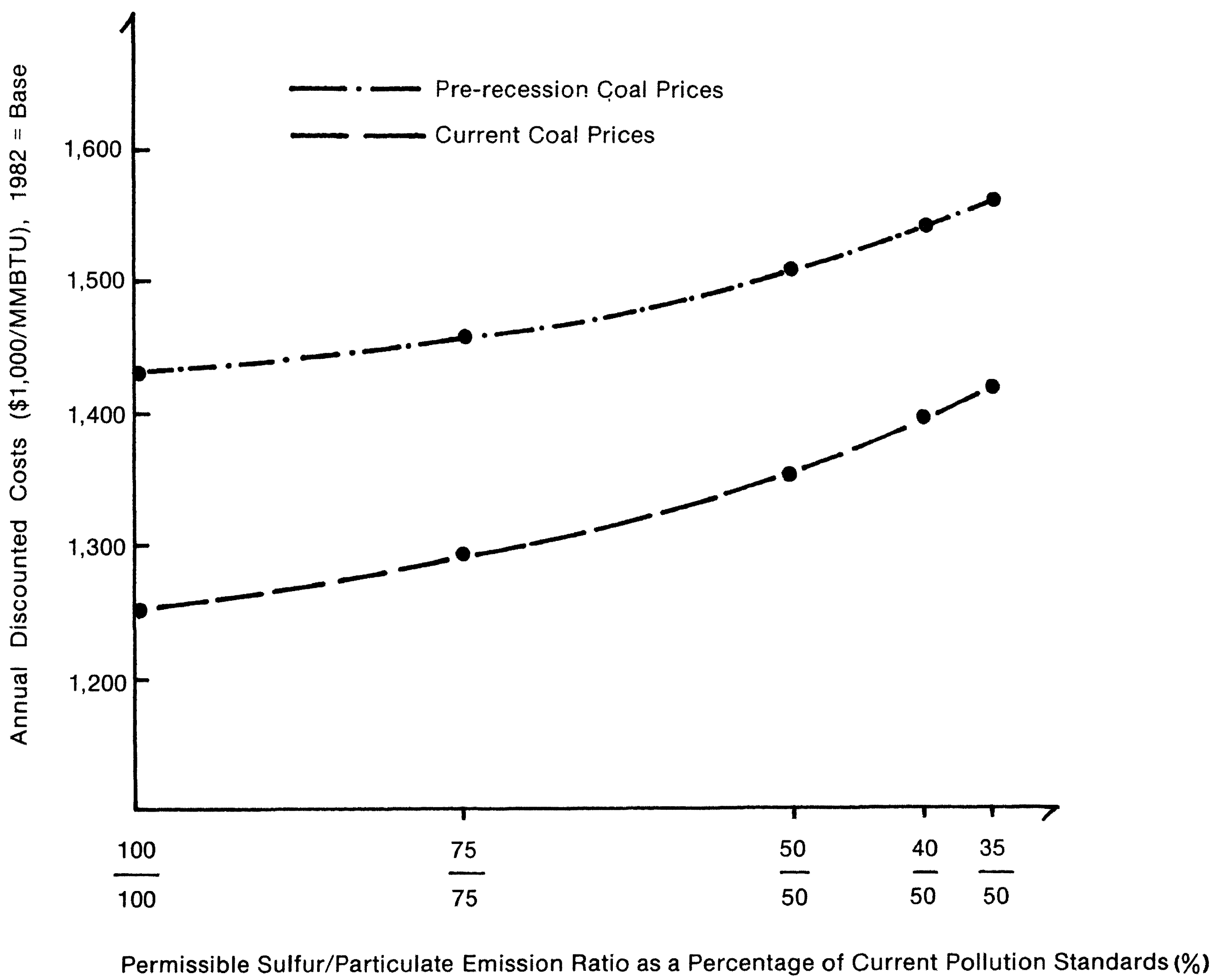

FIG. 6.—Medium boiler's annual costs by air pollution standards.

hold for the low, most likely, and high price growth scenarios. The fact that these results are not consistent with later years, 1990 and 1992, may result from the price gap widening between coal and wood sufficiently in later years to make wood uneconomical.

Wood chips are not economical assuming current coal prices despite the inclusion of pollution abatement costs. However, these costs do affect the optimal type of coal used. The results in Figures 5 and 6 suggest that cleaned coal is the socially desirable, low sulfur coal for Ohio boilers. The social cost analysis also shows that if pollution restrictions tighten, imported Eastern coal may also be used in increasing proportions with cleaned coal to help meet tighter pollution standards. Significantly, Ohio coal never entered the solutions. This fact suggests that Ohio's coal industry will face reduced demand unless a greater proportion of its coal is cleaned. Interestingly, in later project years (1987, 1990, and 1992) cleaned coal became the only optimal boiler fuel as the price gap between cleaned and imported coal widened. Apparently when imported coal prices increase relative to cleaned coal, a switch back to predominantly cleaned coal appears socially desirable over time.

An important question in the above analyses is whether the economic infeasibility of forest chips results from current coal prices being depressed relative to pre-recession trends. Would forest chips become socially feasible if pre-recession coal prices were to return? When the model is run based on pre-recession coal prices, the results for the medium boiler change substantially. At pre-recession price trends, forest chips are used in a wood-coal boiler as of the first project year at 50% or less of the current pollution standards. For all project years and all fuel price growth scenarios at 50, 40, and 35% of current pollution standards, the wood fuel composition is 13, 23, then 28% of total heat output, respectively.

These results suggest that if pre-recession coal prices returned, forest chips as well as wood wastes may be socially optimal fuels if stricter pollution standards are enacted and enforced. The threshold price ratio at which wood enters the solution, the ratio of wood to cleaned coal cost per energy output, is 1.33. It needs to be stressed that stricter proposed federal guidlines do not include this boiler size (40.1 MMBTU/hr); thus it is not probable that such boilers would have to meet the most stringent standard (35%). However, if standards were reduced to 50% of current standards, these results suggest that forest chips may still be socially optimal.

Another pattern shown in the study is that tighter standards will impose large compliance costs on boiler owners. As the permissible emissions drop (moving across Figure 6 from left to right), annual discounted costs increase when either current or pre-recession coal prices are used. These cost increases are incurred due to

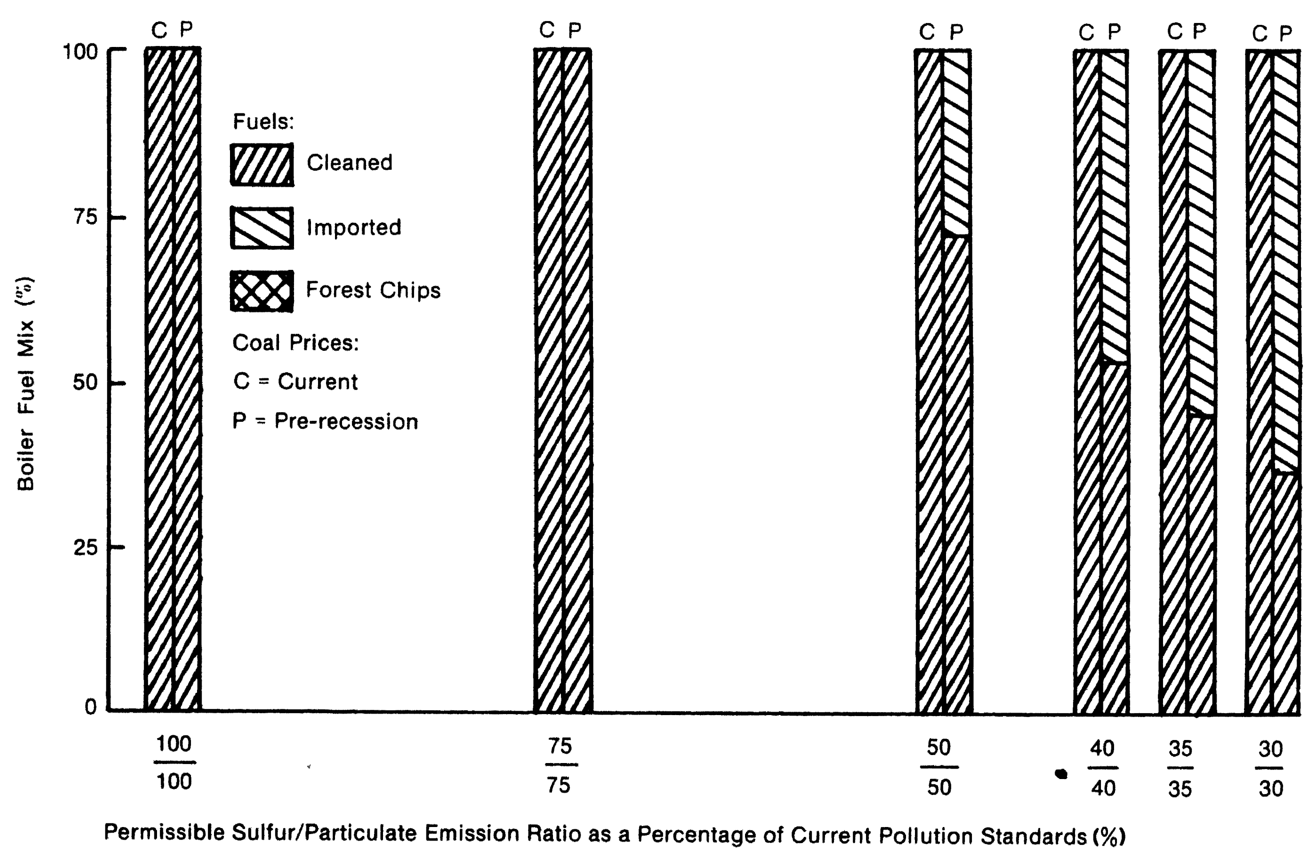

FIG. 7.—Optimal large boiler fuel mix as a percentage of current air pollution standards.

the use of more expensive and effective pollution equipment, the wet scrubber, and the mixing of high priced imported coal or forest chips with cleaned coal. The optimal pollution control equipment at 100% of current standards is a bag house filter; however, as current standards are reduced to 75% or less, a wet scrubber is the optimal equipment. The total costs go up across standards because wet scrubbers have higher capital and operating costs and the fuel mix changes towards higher priced boiler fuels—imported coal or wood. These results indicate that energy users will incur higher compliance costs if stricter standards are enacted and enforced. Some questions not answered in the study are how such costs compare to the social gains from reduced pollution, to what extent will these higher costs be passed on to consumers, what (if any) role should the government or public sector play in easing these costs into the market, and how does the incidence of compliance costs (compliance costs as a proportion of total boiler costs) compare across boiler sizes?

The results of the social analysis for the large-scale system are shown in Figures 7 and 8. As in the case of the medium boiler assuming current coal prices, forest chips never enter the optimal solution (Fig. 7). Even in 1987, 1990, or 1992 using the low, most likely, or high price growth projections, forest chips are never used when coal prices begin at current or pre-recession price levels. The results again suggest that cleaned coal may have an important cost reduction to Ohio boiler users if pollution standards are tightened over the coming years. As with the medium boiler case, the optimal fuel mix favors the use of cleaned coal over imported coal in later years as the price spread between the two types of

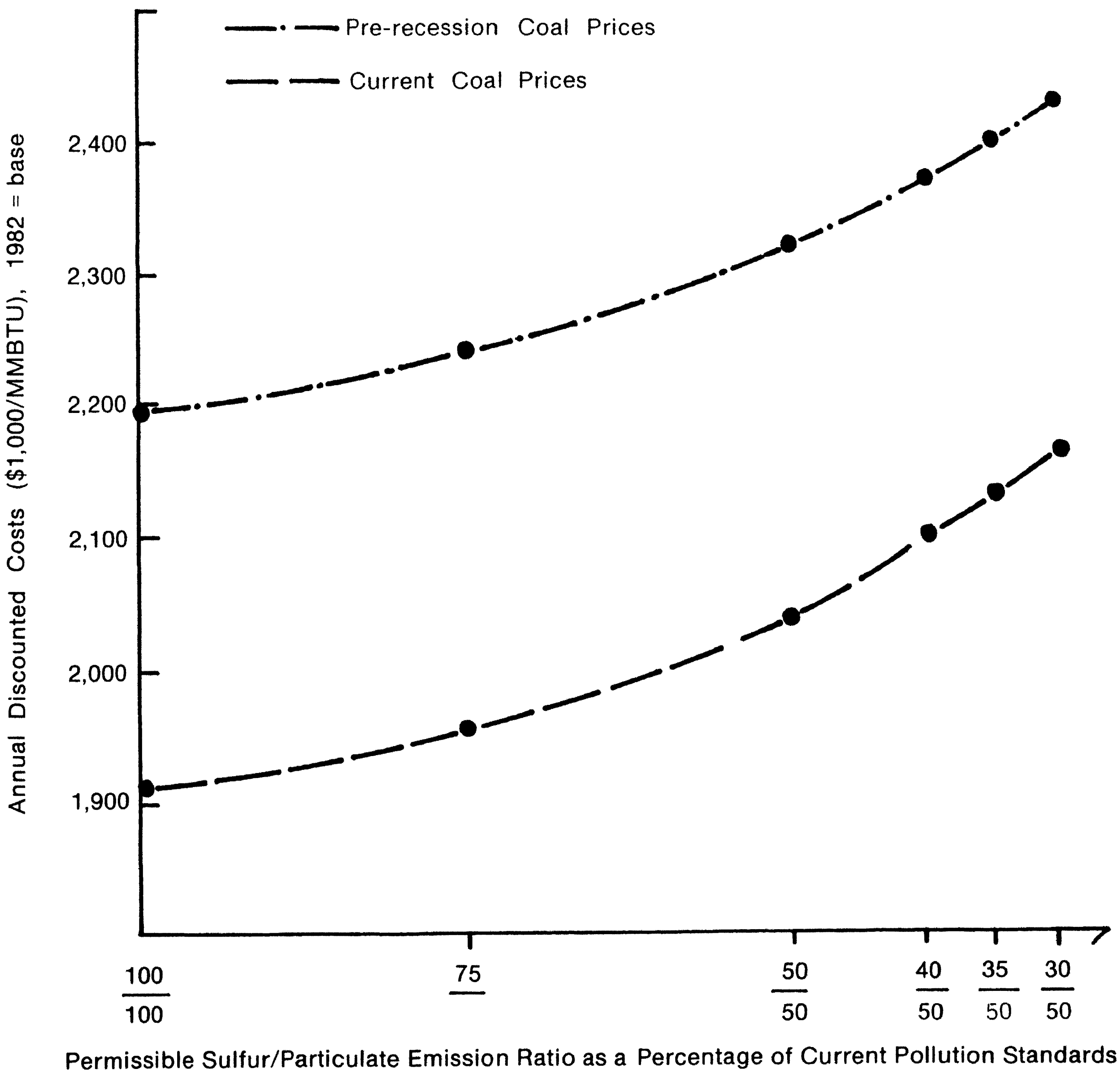

FIG. 8.—Large boiler's annual costs by air pollutions standards.

coal is compounded over time.

Forest chips never enter the optimal solution until year ten (1990), when the relative price ratio per MMBTU output of wood to cleaned coal is 1.30 in the low price projection scenario and assuming pre-recession coal prices. Forest chips appear uneconomical until later in the project life for the large boiler due to higher wood fuel costs relative to coal costs than with the medium boiler. Wood fuel transportation costs are higher than the medium case study by approximately $0.50/MMBTU output.

As shown in Figure 8, as pollution standards tighten, total annual costs go up. Like the medium boiler case, annual discounted costs increase with stricter pollution standards. Assuming current coal price levels, costs go from $1,909,000 at 100% of current sulfur and particulate levels to $2,166,000 per year at 30% sulfur and 50% particulate levels. When historic coal prices are used, total costs rise from $2,218,000 at the strictest standards, or a 20% increase. Costs increase at an increasing rate with stricter standards, implying that stricter standards increase the marginal costs of compliance. Also, similar to the medium case study, the optimal pollution control equipment goes from use of a bag house filter at current standards to a wet scrubber at 75% of current standards for all project years.

These results suggest that forest chips may become economical in medium sized boilers sooner than in larger boilers provided such strict standards are applied to both boilers. Due to the amount of uncertainty regarding enforcement of stricter standards and future fuel price ratios, the possibility of forest chips becoming a dominant boiler fuel for larger boilers in the near future is not supported by these results. Coal prices would need to increase above pre-recession levels before forest chips in the large boiler appear sociallly desirable from an energy user perspective. Other questions about socially optimal fuel use include the employment and income effects of forest vs. coal use, the environmental tradeoffs, and the public sector role in enforcing stricter pollution standards.

SUMMARY OF RESULTS

This study compares the discounted cash flows of wood (wastes, forest or plantation chips), natural gas, and coal boilers at varying air and land pollution compliance levels. Three boiler size case studies, small (2.75 MMBTU/hr), medium (40.1 MMBTU/hr), and large (71.1 MMBTU/hr), are developed and compared under two types of discounted cash flow analyses (financial and economic). The cash flow analysis is based on the inclusion of minimal land and air pollution compliance costs (financial) vs. stricter compliance costs resulting from newly proposed federal guidelines (economic). The economic analysis uses an optimization model to internalize sulfur and particulate emission shadow prices.

In the financial analysis, wood wastes are the cheapest feedstocks, followed by coal, forest chips, natural gas, and energy plantation chips. Given current relative prices for coal, wood, and natural gas, only wood wastes in either wood conversion technologies (gasification or combustion) are always financially competitive with coal. Under current or pre-recession (pre-1982) coal prices, forest chips are presently competitive with coal only when burned in the small gasifier and in the medium gasifier at higher discount rates (15%). Forest chips, however, are financially infeasible compared to coal if burned in all three sizes of combustion boilers, even at higher (pre-recession) coal prices.

The present economic advantage of wood wastes as the attractive wood feedstock for combustion boilers is put in perspective by its supply constraints. Using Hall's estimates of Ohio's wood waste potential (12), sawmill and logging residues could provide about 4% of Ohio's 1982 industrial natural gas demand and 3% of Ohio's direct industrial coal demand (27). Besides its limited supply, current prices for wastes would be expected to rise if a large wood energy market developed. However, since the break-even price difference between wood wastes vs. coal conversion is approximately $2.00/MMBTU output (wood gasification) or $1.00/MMBTU output (wood combustion), average wood waste prices could go up 50 to 100% before wastes would be financially infeasible.

In contrast to wood combustion, wood gasification systems using either wood wastes or chips are financially quite attractive when compared to natural gas or coal boilers. Only the medium scale gasifier using forest chips was financially infeasible compared to coal at current or pre-recession coal prices, although it became feasible at a 15% discount rate assuming pre-recession coal prices. This result suggests that wood gasification could be the most competitive wood conversion technology in the immediate future.

In the economic analysis, tightening pollution standards for combustion boilers does not make forest chips competitive with cleaned Ohio or imported Eastern coal at current coal prices. Whereas wood wastes are also the cheapest feedstocks in the economic analysis, only when pre-recession coal prices are used do forest chips become economical. Raising coal prices to pre-recession levels and tightening pollution standards in the economic analysis results in forest chips being feasible for the medium but not large boiler. If pre-recession coal prices are assumed, forest chips are mixed with cleaned coal in the medium boiler when current air pollution standards are reduced to 50% or lower of current standards. Chips, however, are not used until the tenth year in the large boiler scenario even if pre-recession coal prices are used.

In general, enforcing stricter pollution standards at current coal prices shifts combustion fuel reliance from cleaned Ohio coal to a mixture of cleaned and imported Eastern coal, changes pollution control equipment, and raises annual costs. Ohio's high sulfur coal never enters the solution for either boiler. Annual costs rise due to the use of more expensive pollution control equipment and the mixing of more costly imported low sulfur coal or forest chips with cleaned coal. Varying discount rates and fuel price growth levels do not have much effect on these general patterns.

In comparing wood fuel feasibility, hardwood plantations are simply not economical as boiler fuels given current relative fuel prices. A major reason for their infeasibility is the high planting and site preparation costs. These costs make up more than 55% of total costs. In comparison, stumpage costs for forest chips represent only 8% of total harvest and transportation costs. Technological breakthroughs for increasing yields and/or decreasing costs appear necessary before wood plantations in Ohio can be competitive with forest chips or coal.

POLICY IMPLICATIONS

The results of this study have policy implications for four general areas—forestry, coal mining, environmental regulation, and Ohio's energy future. Each general area would be affected if wood energy use increases and a tightening of environmental standards occurs in Ohio. These implications, of course, are constrained by the limited ability to generalize from three case studies to all boiler users in Ohio.

Forest Industry

The lack of economic and financial viability of forest chips over coal given current coal prices suggests that Ohio's loggers will not have a significant industrial energy market in the near or perhaps intermediate future. While some boilers may switch from natural gas to wood, the present excess supply of and low prices for wood wastes mean that these wood sources should be used before forest chips. Forest chips appear economical only if pre-recession coal prices return and stricter air quality standards are enforced. Even then, chips are economical only for the medium boiler size. For Ohio loggers, the wood boiler market simply does not become strong unless important coal price and environmental regulation changes occur. Given that forest chips are economical only at much higher coal prices, low quality wood producers may need to look to other markets for expansion such as the residential fuelwood market.

In contrast to forest chips, Ohio's wood wastes, although limited in supply, have an important energy role in providing small to medium energy users with a sustainable low cost fuel. Hall *et al.* (12) stress the importance of Ohio's waste wood supply as another energy source for boiler users. Although limited in supply, its importance particularly to small to medium scale users will be critial in terms of annual cost savings. Wood product industries could gain from the sales of their waste products to these energy users.

Coal Mining

The dominance of cleaned or low sulfur imported coal in the economic analysis optimization model, at either current or stricter air pollution standards, has important implications for Ohio's coal mining industry. If the enactment and enforcement of stricter pollution standards occurs, Ohio's high sulfur coal industry could face a serious drop in demand. To prevent a loss in coal revenues plus secondary impacts in employment and income on the coal mining region, the state will need to encourage cleaning a greater percentage of Ohio's coal. At present 35 coal cleaning facilities exist in Ohio, with a potential of cleaning far more than is currently being cleaned. These plants are being underutilized due to the low demand for cleaned coal and problems involved in coordinating coal company interactions. If stricter pollution laws are enforced, cleaned coal may become financially more attractive than uncleaned Ohio coal since the latter coal requires high flue desulfurization costs. This implicit price difference may be sufficient to overcome current problems in the coal cleaning industry. If not, public policies may be needed to encourage cleaning of Ohio coal due to the latter's regional and economic impacts.

Environmental Regulations

The importance of environmental regulations on changing optimal fuel mixes and the maintenance of sustainable harvests has been shown by this study. Stricter air quality regulations will impose increasing costs on boiler operations and alter the boiler fuel dependence to different types of coal. While the state may be interested in the secondary impacts (employment and income) associated with a decrease in Ohio coal use, private energy users will be motivated by the lower costs of cleaned or imported coal vs. the cost of expensive poillution abatement equipment. As environmental regulation forces the adoption of pollution abatement equipment, concurrent emphasis on research and development to decrease the costs of such technologies might also be considered.

While this study does not foresee the use of forest chips as a competitive boiler fuel in the near future, except perhaps in small or medium gasifiers, environmental policy implications also emerge from the costs of maintaining sustainable harvests. Reducing cutting cycles to only 20 years through overcutting of forests, extremely short rotation lengths for Ohio, would rapidly reduce the long-run quality and supply potential of Ohio's forests. Given the long-run effect on Ohio's forests from this reduction and the fact that only \$2 to \$3 per green ton may be saved in total transportation costs by this reduction, it could be that the private market valuation of maintaining sustainable harvests does not reflect its user cost or long-run scarcity value. If a strong wood chip energy market were to develop, environmental regulation might be considered if the state felt it socially desirable to maintain a sustainable wood supply in Ohio.

Ohio's Energy Future

This study suggests that coal rather than wood will have an important energy role for Ohio in the coming decade. Wood wastes may be a low cost, important fuel alternative for small to medium industries or institutions, but wastes from wood manufacturing firms simply cannot provide a significant proportion of Ohio's boiler energy needs. Only when stricter pollution standards exist and pre-recession coal prices are resumed do forest chips appear economical in combustion boilers. However, energy policies encouraging research and development of wood gasification, as compared to combustion, could provide Ohio with a financially viable alternative to coal boilers which might utilize forest chips. Even though wood gasification appears the most commercially attractive wood energy conversion, the potential forest energy use will probably never exceed Ohio's coal use unless wood plantations become economical. Thus, coal can be expected to play an integral role in Ohio's energy future even if wood chips become competitive in the future.

In conclusion, only wood wastes and wood gasification, wood energy supply, and conversion technology appear economical at present. Given currently depressed coal and fossil fuel prices, the short-term viability of wood chips and expansion of their market to the energy area simply do not appear feasible. However, if future energy prices exceed pre-recession trends, economic recovery strengthens, and stricter air pollution standards are enacted and enforced, wood may be a desirable boiler fuel.

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APPENDIX A
FUEL PRICE GROWTH SCENARIOS

TABLE A-I.—Projected Real Fuel Price Growth Scenarios by Years.

Project Years	Annual Real Fuel Price Growth Scenarios (Annual Percent)								
	Low			Most Likely			High		
	Wood	Natural Gas	Coal	Wood	Natural Gas	Coal	Wood	Natural Gas	Coal
1-4	-2	8	3	0	12	5	2	14	7
5-9	1	10	5	2	16	7	6	20	9
10-20	2	13	7	2	12	7	8	16	9

Source: Table I.1, Appendix I (36)

APPENDIX B
FUEL AND EQUIPMENT COSTS

TABLE B-I.—A Comparison of Field Data vs. Budgets on Average Annual Harvest Costs for High Volume Large-scale Producers (1982 Dollars per Green Ton).

Cost Category	Large Volume Producer Haggard*	Budgeted Systems† I	Budgeted Systems† II	Averages
		($/green ton/year)		
Equipment	353	520	571	481
O+M	313	268	283	288
Labor	4.88	351	4.51	430
Fuel	2.48	345	325	348
Miscellaneous‡	136	145	140	140
Stumpage	100	100	1.00	100
Total	16.38	1719	1870	1687

*Haggard, J. W. (11) Data come from Table 2, p 43, and represent averaged annual 1979-80 costs inflated by 25% for 2.5 years Operations and maintenance costs are Haggard's maintenance and repairs plus supplies categories.

†System I uses a large whole tree chipper, Morbark 22, one feller-buncher, and grapple skidder; System II uses a Morbark 22 but only cable skidders.

‡Miscellaneous includes taxes, insurance coverage, owner's salary, and accountant fees.

TABLE B-II.—Delivered Prices for High Sulfur Ohio and Low Sulfur Eastern Kentucky Coal in Nominal, Real, and Energy Input Terms (1978-1982).

User	Year	Ohio Nominal ($/st)	Ohio Real* ($/st)	Ohio Energy Input ($/MMBTU)	Eastern Kentucky Nominal ($/st)	Eastern Kentucky Real* ($/st)	Eastern Kentucky Energy Input ($/MMBTU)
Electric Utility							
	1978	26 91	16 02	0 72	31 01	18 46	0 76
	1979	27 91	14 93	0 67	33 60	17 97	0 74
	1980	31 54	14 88	0 67	38 65	18 23	0 75
	1981	34 52	15 21	0 69	43 52	19 17	0 79
(current)	1982	28 00†	11 07	0 50	40 20†	15 89	0 66
(historic)**	1982	39 31	15 57	0 70	48 98	19 36	0 80
Industrial							
	1981	37 56	16 55	0 75	N A	N A	N A
(current)	1982	31 00†	12 25	0 55	43 47‡	17 18	0 71
(historic)**	1982	42 12	16 65	0 75	52 04	20 57	0 85

Source Ohio Department of Energy 1982 *Coal Prices* Columbus Ohio

*Base year is 1970 using Consumer Price Index from USGPO *Economic Indicators* 1970 through November 1982 Washington D C

†These figures were obtained from talking with coal users and mining operators

‡Figure was estimated by adding $0 05/MMBTU to current 1982 price

**Historic price trends are derived by inflating 1981 coal prices to 1982 levels These historic levels reflect the projected price trends or patterns up to the 1982 recession

TABLE B-III.—Annual Pollution Abatement Equipment Costs.

Pollution Abatement Equipment	Boiler Size Medium	Large
	($1,000/year)	
Multicyclone Collectors		
Annual Capital*	19 0	28 8
Annual Operating	31 0	43 5
Bag House Filter		
Annual Capital*	90 3	107 0
Annual Operating	113 4	152 0
Wet Scrubber		
Annual Capital*	63 9	71 9
Annual Operating	193 0	245 0
Electrostatic Precipitator		
Annual Capital*	128 0	142 0
Annual Operating	140 0	155 0

*Capital costs are based on 15% interest rate assuming equal annual payments

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